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Design and Operation of Four Prototype Fire Detection Systems in Noncoal Underground Mines

By William H. Pomroy and Robert E. Helmbrecht

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

Å	angstrom	min	minute
c/s	cycles per second	nA	nanoampere
°C	degree Celsius	Ω	ohm
eV	electron volt	ppm	parts per million
ft	foot	pct	percent
°F	degree Farenheit	V	volt
h	hour	V ac	volt, alternating current
in	inch	V dc	volt, direct current
m/s	meters per second	W	watt
mA	milliampere	yr	year
mCi	millicurie		

DESIGN AND OPERATION OF FOUR PROTOTYPE FIRE DETECTION SYSTEMS IN NONCOAL UNDERGROUND MINES

By William H. Pomroy [1] and Robert E. Helmbrecht [2]

ABSTRACT

Fires in underground metal and nonmetal mines pose a threat to the safety of underground miners and to the productive capacity of this Nation's mines. Contaminated air (smoke, carbon monoxide, and other products of combustion) is the primary life safety hazard created by a mine fire. The most reliable defense against the hazard posed by the rapid spread of contaminated air underground is early warning fire detection and rapid evacuation. This Bureau of Mines report describes the design and operation of four prototype early warning fire detection systems, for underground noncoal mines, presently undergoing prolonged in-mine testing by the Bureau. The systems are described within the context of the underground mine environment.

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INTRODUCTION

Fires in underground noncoal mines pose a serious threat to the safety of underground miners and to the productive capacity of this Nation's mines. The potential for loss of life and interruptions to production due to fires is often underestimated, even within the mining community and despite documented fire statistics to the contrary.

This misconception was addressed by a senior Mine Safety and Health Administration official (1):[3]

> Over the years there has developed a generally accepted opinion that major disasters from fires do not occur in noncoal mines. The Sunshine Mine disaster should have erased that opinion. Fires in mines are not unusual. We have a continuing history of fires in North American mines.
>
> Historically, timber has been the primary source of fuel in the major mine fires, and mine operators at properties that do not use timber for ground support tend to believe they do not have a potential fire problem. Let us point out now that there are other sources of fuel for combustion. So long as internal combustion engines, electrical equipment, lubricant storage, fuel stores, combustible hydraulic systems, warehousing of combustible solvents, combustible ventilation tubing, and timber support are necessary to our mining systems, the potential of mine fires remains.

Indeed, since 1965, over 150 fires accounting for 119 fatalities have been reported in underground noncoal mines (2). Countless millions of dollars have been spent on rescue and recovery, equipment repair and replacement, and mine rehabilitation. In addition, mines shut down by fires have been forced to forego hundreds of millions of tons of mineral production.

Contaminated air is the primary life safety hazard in an underground mine fire, accounting for over 78 pct of mine fire deaths since 1945 (3). Ventilation streams carry smoke, carbon monoxide, and other toxic fire gases to areas of the mine remote from the fire itself, thereby exposing miners who may be widely scattered throughout the working to toxic fire gases.

One means of defense against the hazard posed by the rapid spread of contaminated air is early warning fire detection and rapid evacuation. The data show that fires detected within 15 min of development result in little or no damage to the mine in 73 pct of all cases (2). Effective, reliable detection systems, capable of detecting fires at their early, or even incipient stages, can significantly improve mine safety by ensuring adequate time for mine personnel to follow appropriate emergency procedures. Since 1968, however, only about one-third of reported fires were detected within 15 min (2).

This Bureau of Mines report describes the design and operation of four prototype fire detection systems developed for noncoal underground mines. Results of prolonged in-mine testing and system design refinements will be presented in a subsequent report.

The body of this report contains four sections, each describing one of the prototype detection systems. The detection instruments employed in this research program, several of which are common to more than one detection system, are described in detail in the appendix.

FIRE DETECTION SYSTEM FOR A TIMBERED SALT MINE SHAFT

Although all mine fires present the potential for disaster, fires in mine shafts are particularly hazardous because rapid and safe egress of miners and proper mine ventilation can be seriously impaired by shaft fires. A recent study of mine fires shows that since 1950, about 9.7 pct of all mine fires occurred in shafts, but about 17.6 pct of all mine fire fatalities were attributed to shaft fires (2).

[3] Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

Carbon monoxide, carbon dioxide, and submicron particulate detectors used separately or in combination, have been used successfully to provide early warning of shaft fires (4), however these detectors require occasional maintenance and calibration. Industrial-grade thermal fire detection devices are generally characterized by high reliability and durability but low maintenance requirements, even when used under the harshest conditions. Clearly, these attributes are desirable for mining applications.

One limiting feature of thermal detectors is that they rely on convected thermal energy for response. The distance between the detector and the fire, the relative spatial orientation and placement of the detector relative to the fire, and local air currents profoundly affect detector performance. Thus, in order to provide for large area coverage, numerous closely spaced detectors are required. A common example of thermal detection in the mining industry is the typical conveyor belt fire detection system mandated for underground coal mines (5). Spot-type, thermal detectors, spaced at 125-ft intervals along the entry provide early warning of a belt fire.

A string of spot-type detectors arrayed in a similar manner in a mine shaft is a feasible approach to shaft fire detection, however, the use of a line-type device would offer superior performance. A line-type device senses the heat from a fire at any point along its length. It can be thought of as spot-type detection in the limiting case where the distance between adjoining detectors equals zero.

Limited success has been achieved using fusible contact line-type thermal sensors in shafts (3). However, fusible contact line-type sensors are subject to occasional false alarms and considerable effort may be required to restore the detector to proper operation following an alarm, especially if the contact occurs in a section of the shaft for which access is difficult. An alternative to the fusible contact detector is thermistor strip.

A prototype thermistor strip fire detection system for mine shafts was developed by the Bureau and installed in the 1,200-ft main production shaft of a salt mine in Detroit, MI. The system was installed along the entire length of the shaft (fig. 1). The detector is described in detail in the appendix.

The system provides two alarm temperature settings, permitting a prealarm at a lower temperature and an alarm at a higher temperature. The system also includes a hotspot indicator that pinpoints the location of the overheated area and provides digital readouts of the distance between the shaft collar and the hotspot.

The system has three main subsystems: the sensor element in the shaft, the system control panel in the headframe-crusher building, and an alarm annunciator panel in the hoist house. The detector is positioned roughly in the center of the two-compartment shaft. It is attached at each timber set with special mounting brackets, thereby providing support for the detector at approximately 4-ft intervals. The detector is divided into two zones, the upper zone and the lower zone, with the two thermistor cables joined in a junction box at the shaft midpoint (fig. 2). The system control panel (fig. 3) contains all control circuits, backup power supply, and means for calibrating and troubleshooting the system. The annunciator panel (fig. 4), within sight of the hoist operator, provides a green lamp indicating normal system operation, visual and audible indication of prealarm and alarm conditions, and a digital display of the hotspot location.

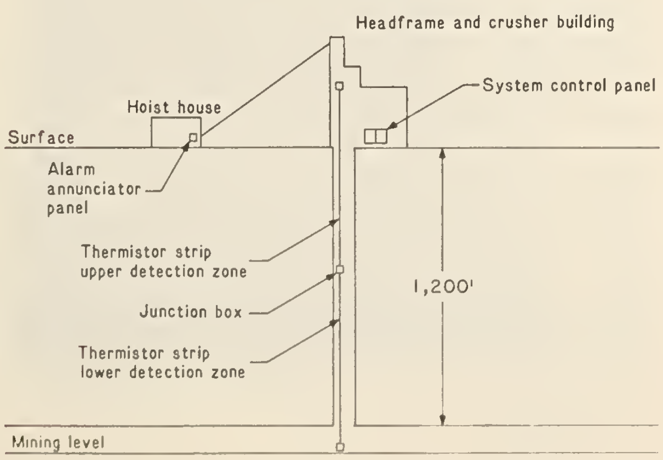

FIGURE 1. - Layout of shaft fire detection system.

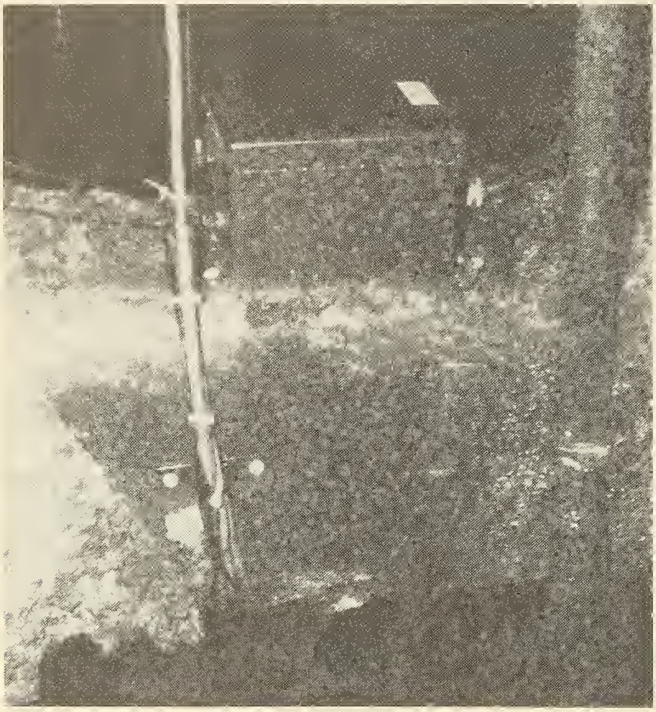

FIGURE 2. - Thermistor strip shaft fire detector and junction box attached to shaft timber.

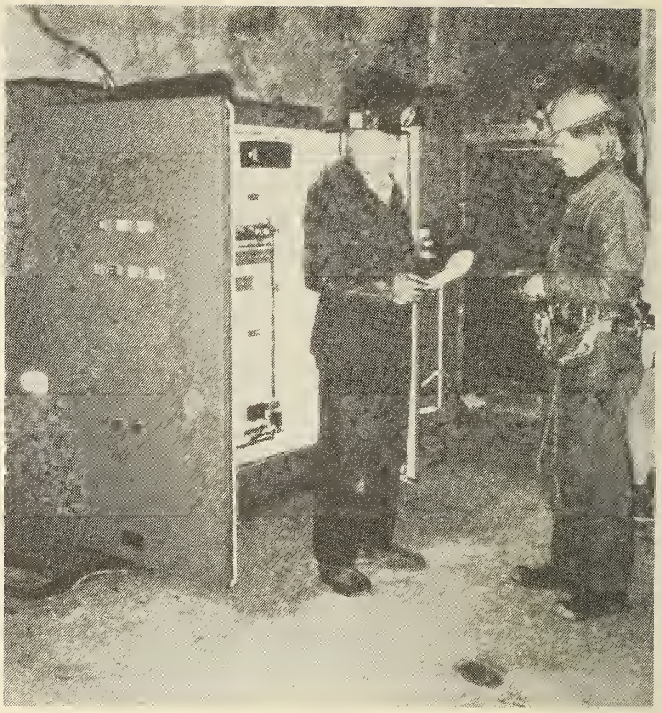

FIGURE 3. - System control panel in headframe building.

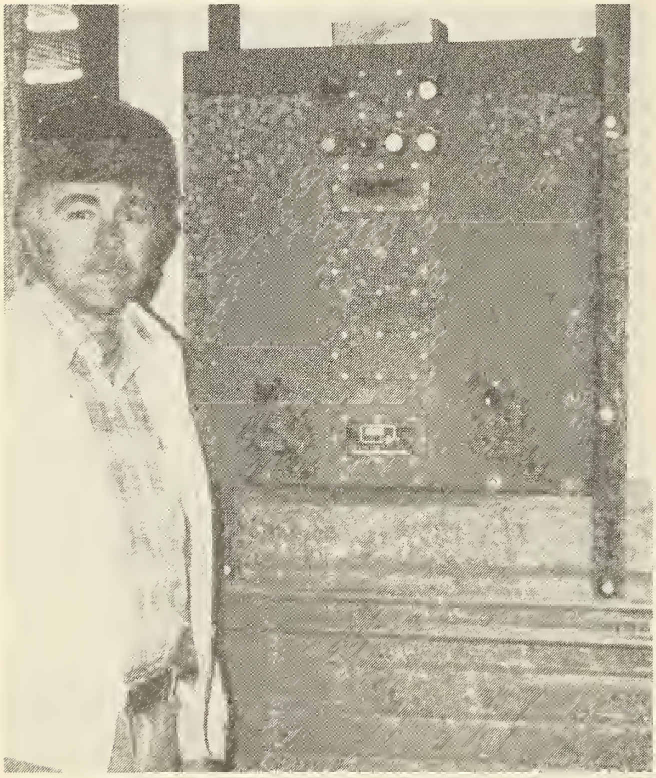

FIGURE 4. - Shaft fire detection system annunciator panel in hoist house.

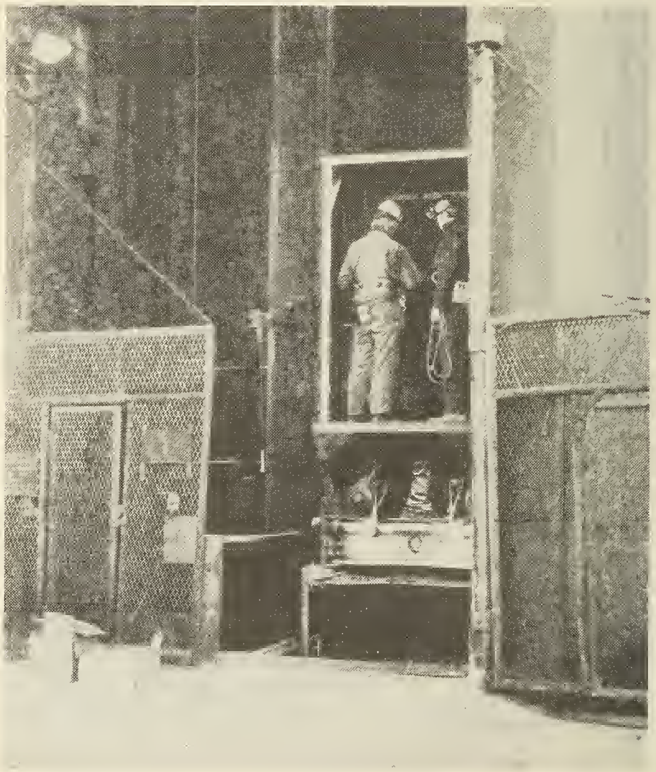

FIGURE 5. - Installation of thermistor strip shaft fire detector from a canopy above the man cage. Cage doors are open for illustration purposes only.

The system was completely installed by a three-person crew over a 4-day period in April 1982. The detector was installed from a platform above the skip (fig. 5) by interconnecting ten 120-ft detector segments end to end. Because this shaft is the main mine exhaust, the air is laden with salt. This highly corrosive atmosphere is detrimental to the operation of electrical systems, necessitating great care in hermetically sealing each detector segment interconnection with a silicone adhesive-sealant. All external parts of the detector wire and connections are stainless steel which has been further protected with a corrosion-resistant Teflon[4] fluorocarbon polymer jacket. The control panel and annunciator panel are housed in dust-tight enclosures. Following installation, the system was functionally tested. At a known elevation in the shaft, a propane torch was used to heat a section of the detection cable. The prealarm and alarm functions operated properly and the hotspot indicator displayed the correct elevation (fig. 6).

The system was operated continuously from April 1982 until June 1983 without hardware failure. Once during that period, a lightning strike at the headframe structure caused a momentary alarm, however, the system returned to the normal operating mode without further incident. These preliminary test results are significant because they indicate that the hardware and installation precautions are suitable for this worst case corrosive environment.

In June 1983, mine officials reported a system failure. A technician was dispatched to the mine to inspect the system, determine what repairs and/or equipment replacement were required, and recommend system modifications (if any) needed to avoid future similar problems.

The technician found that four 120-ft detector segments in the shaft had been ripped from their mountings by an object

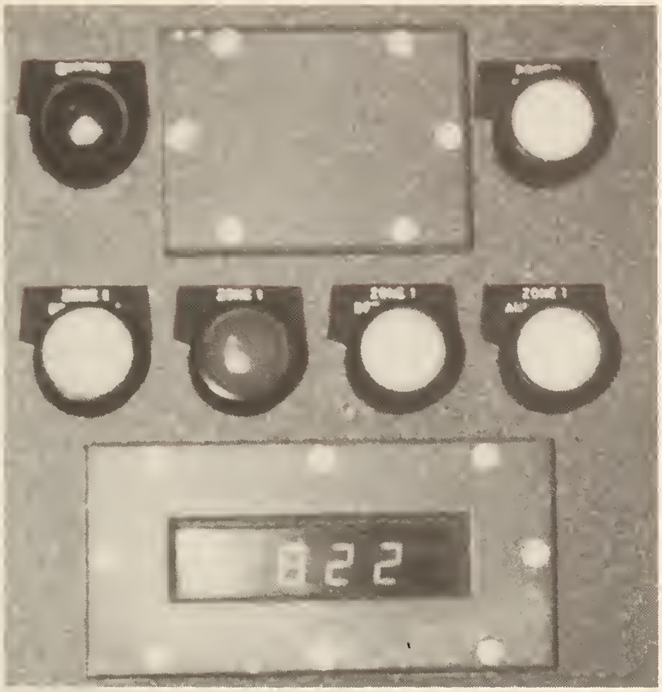

FIGURE 6. - Annunciator panel during system test showing alarms and digital hotspot indicator.

protruding from the skip. All four segments needed to be replaced. As a precaution to prevent further damage in the future, it was recommended that a 1/8-in-diam stainless steel messenger cable be installed in the shaft parallel to the detector and flush with the timber sets. The detector could then be removed from the mounting brackets and attached to the messenger. This mounting arrangement would (1) draw the detector closer to the timber sets so that it will be less likely to become entangled with objects protruding from the skip, (2) permit the detector to be secured at intervals closer than the 4-ft spacing of the timber sets, and (3) provide greater overall strength to the installation because the stainless steel messenger cable is much stronger than the detector.

Repairs to the damaged portion of the detector have been delayed because of a production shutdown at the mine. Replacement of the damaged segments and installation of the messenger will be effected and testing continued upon reopening of the mine.

[4]Reference to specific products does not imply endorsement by the Bureau of Mines.

SMOKE DETECTION SYSTEM FOR A MULTILEVEL COPPER MINE

One of the earliest products of incipient combustion is submicrometer sized particulates, or smoke (6). Smoke detection systems that are capable of reliably detecting these particulates are extremely valuable because fires can be detected before they reach the flaming combustion stage. With the aid of such systems, emergency procedures, such as personnel evacuation and fire fighting efforts, can be undertaken at the earliest opportunity, often before the fire poses a direct threat. A complete prototype smoke detection system was designed, fabricated, and installed in an Arizona underground copper mine for prolonged testing and evaluation.

The system consists of 10 detection instruments (fig. 7). Each detector is equipped with a digital telemetry module (mounted in detector cap, figure 8) to convert the detector's analog output to a digital word for transmission of the detector value along with a unique address and verification words to the system control unit. A microcomputer system control, a line interface control module for communication to the computer through an industry standard protocol (RS232C), a disk drive to store the control program and detector output records, a color video display with graphics to highlight alarms, and a printer to provide hard copy of alarm and fault messages are also provided.

The detectors are linked to the system control by a single-pair closed loop telemetry circuit. Connecting outstations in a closed loop minimizes cable costs and installation time and provides a redundant signal path for uninterrupted signal transmission in case of a broken telemetry line.

The system was completely installed by a 4-person crew over a 1-week period (fig. 9). Minor debugging was required following installation because of problems with several telemetry modules, however, the necessary repairs were effected on-site during the week following the installation.

The system operated for approximately 1 yr with a simplified control program while the final version of the control software was developed and debugged. During this period, system operation was limited to a video display of real-time detector outputs and an audible alarm and printout whenever any detector output exceeded its individually programed alarm threshold.

The final version of the control software provides, in addition, video graphics of the detector locations on color mine maps (fig. 10), simple instructions and three-key coded function commands (fig. 11), and alarm, fault, and troubleshooting messages.

FIGURE 7. - Mineworthy ionization-type combustion particle (smoke) detector.

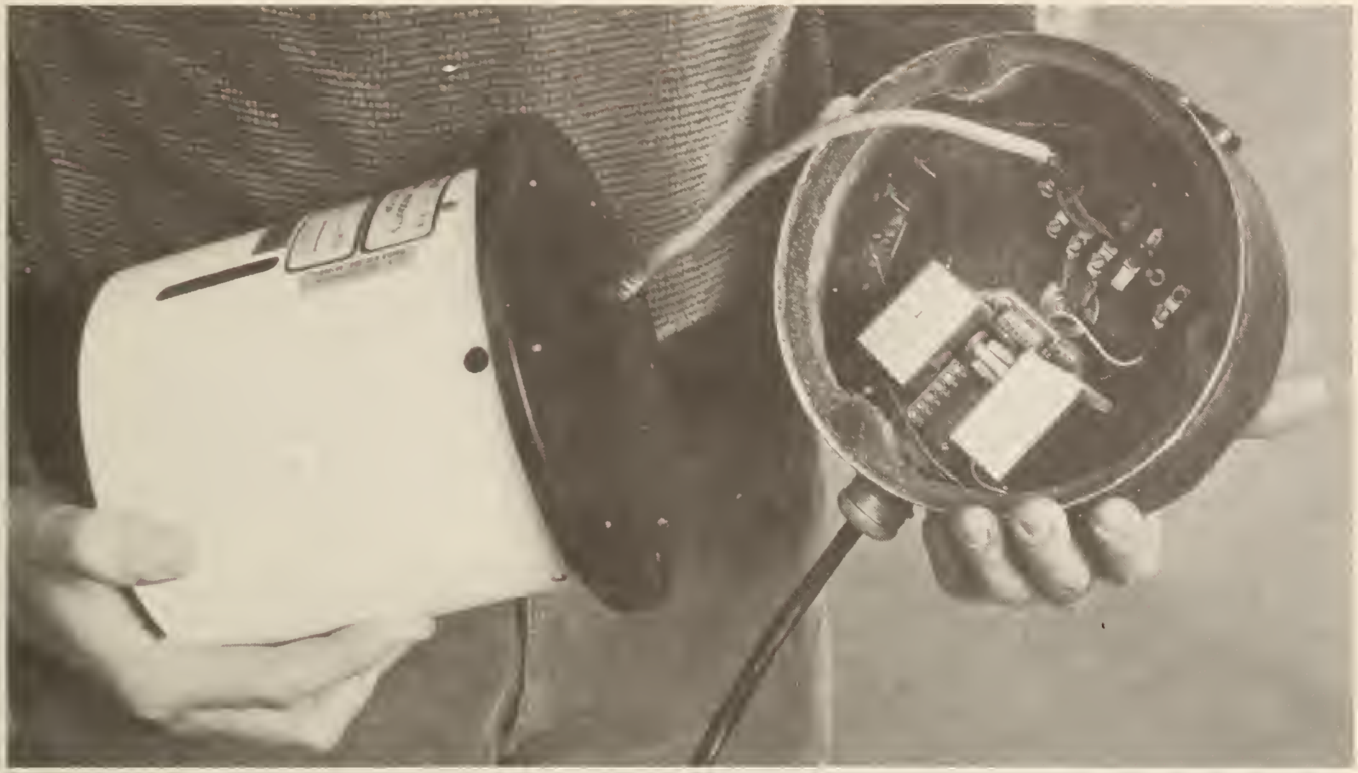

FIGURE 8. - Digital telemetry module mounted inside detector cap.

FIGURE 9. - Installation of ionization-type combustion particle (smoke) detector at the 500-250 ramps.

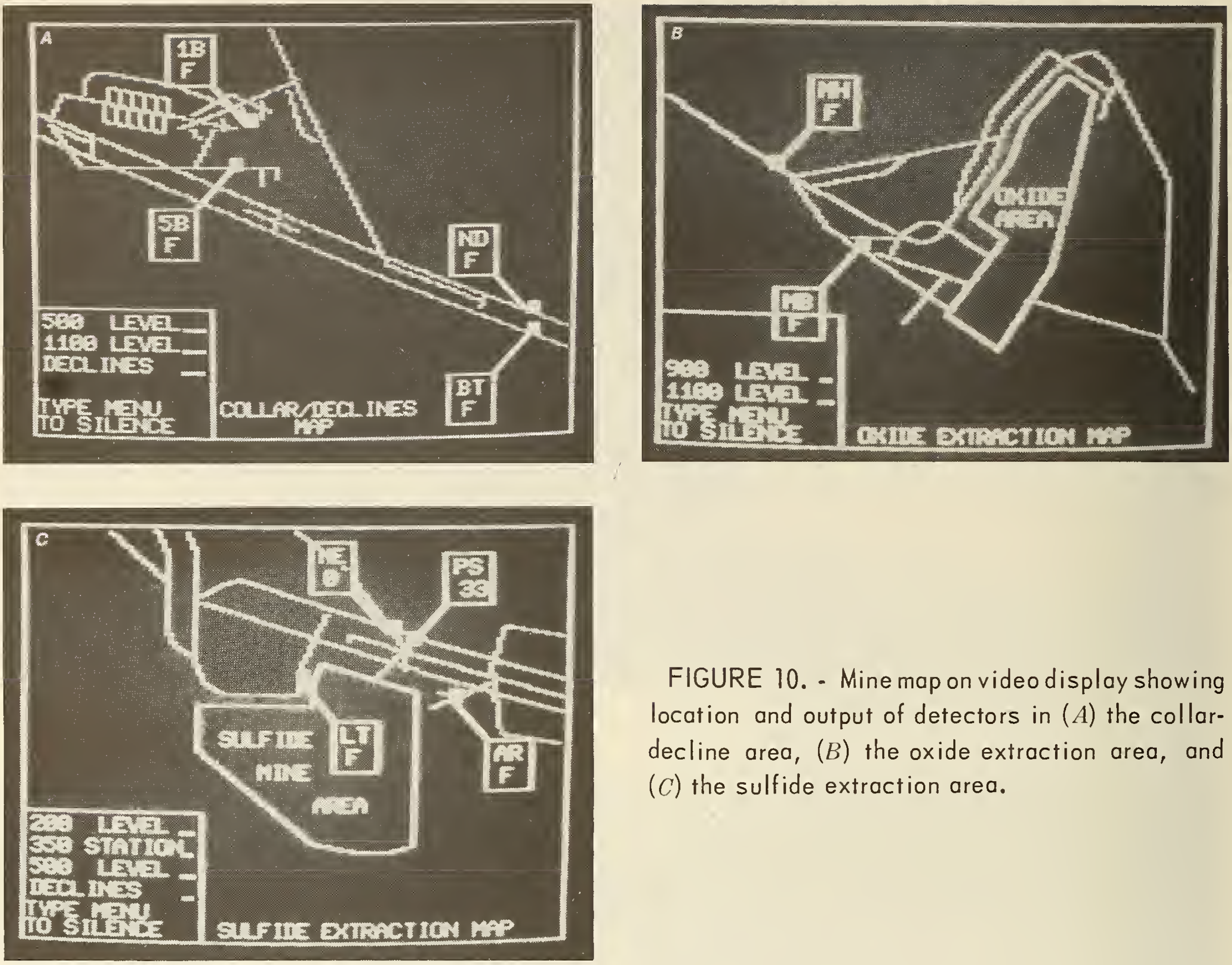

FIGURE 10. - Mine map on video display showing location and output of detectors in (*A*) the collar-decline area, (*B*) the oxide extraction area, and (*C*) the sulfide extraction area.

Following the on-screen prompts and using the simple three-key commands, operators can display one of three mine maps covering the system, change any sensor alarm threshold, display current alarm thresholds, display 72-h sensor history in tabular or graphic form, and manually control the printer.

During the first 3 months of system operation (using the simplified control program) numerous false alarms were issued. The detector-mounted digital telemetry modules, which are susceptible to low voltage conditions, were found to be the cause. Boosting line voltage slightly corrected the problem.

The system has operated for approximately 7 months with the final version of the control software. Minor debugging has been required; however, during this period, three abnormal events (smoking rubber drive pulleys on two pumps and a smoking electrical controls enclosure) were detected by the system.

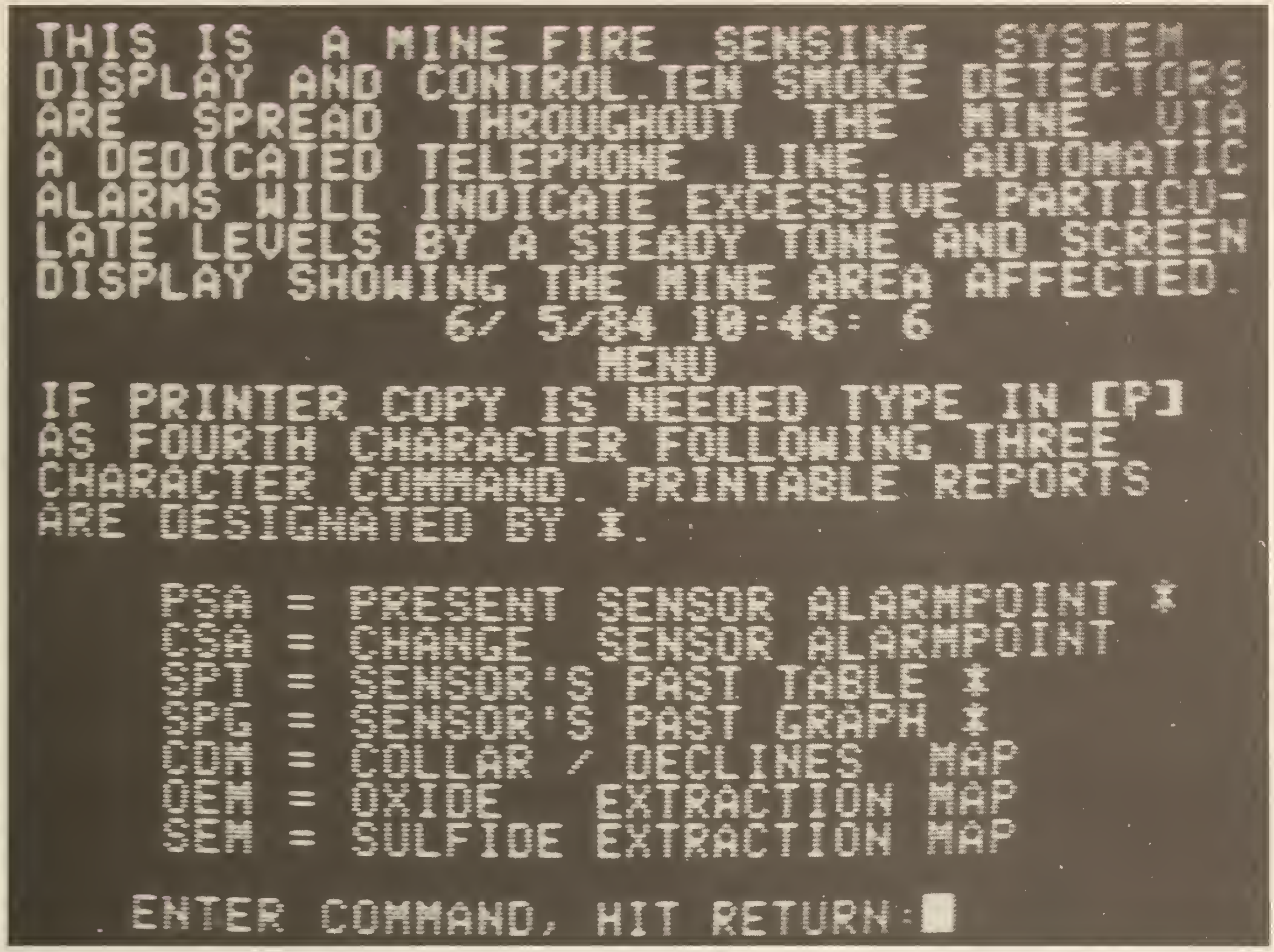

FIGURE 11. - Video display showing three-key function commonds.

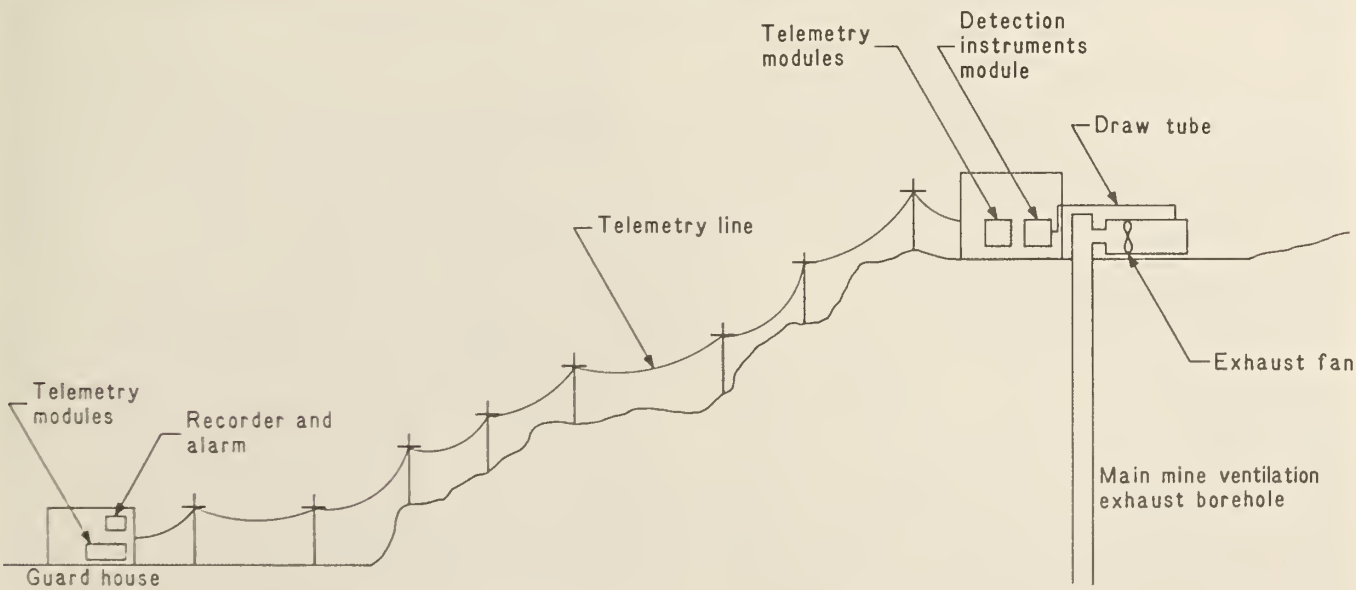

FIGURE 12. - Loyout of mojor elements of spontoneous combustion detection system.

SPONTANEOUS COMBUSTION FIRE WARNING SYSTEM FOR A DEEP SILVER MINE

By definition, spontaneous combustion is the outbreak of fire in combustible material that occurs without application of direct flame and is usually caused by slow oxidation processes under conditions restricting the dissipation of heat. Historically, several disastrous noncoal mine fires have been attributed to the spontaneous combustion of wood or of wood and ores in remote, inactive or sealed areas of mines (7). Overall, spontaneous combustion accounts for only about 2 pct of all underground metal and nonmetal mine fires. However, the potential seriousness of spontaneous combustion fires is understated by this statistic. Fire fighting, mine rescue and recovery, and related operations are complicated by the difficult access to the remote areas where spontaneous combustion fires occur. Since 1950, over half of all underground metal and nonmetal fires lasting longer than 24 h were caused by spontaneous combustion. Associated with the spontaneous combustion problem are still other incidents involving ignition of sulfide dusts, combustion of AN-FO heated by surrounding hot ground surfaces, and the continuous heating of mines utilizing backfill with a high sulfide content.

Recognizing the hazard of spontaneous combustion, the Bureau initiated a research program in 1978 to develop a spontaneous combustion fire warning system for deep metal mines (8). The program began with a comprehensive search of the published literature for reports dealing with spontaneous combustion in mines. In addition, industry experts were contacted in an effort to acquire relevant unpublished research findings. This data base, together with the results of a series of laboratory experiments of the spontaneous heating characteristics of various sulfide ores, timber, and other mine combustibles, supported the development of a conceptual design for a spontaneous combustion fire warning system. The studies indicated that the earliest warning of a spontaneous heating event could be achieved by sensing for long-term trends in the levels of carbon monoxide, carbon dioxide, sulfur dioxide, oxygen, and temperature. A prototype system comprising appropriate detection instruments (details in appendix), telemetry, and recorders was designed, fabricated, laboratory tested, and in-mine field tested at two mines.

Initial in-mine testing was conducted in 1979 in an underground copper mine in Arizona. Results of this phase of the in-mine testing program are described in reference 8. Follow-on testing of a slightly modified system (the Arizona studies indicated that sulfur dioxide detection could be eliminated) was initiated in 1981 at an underground silver mine in Idaho.

This system was installed on surface in an emergency escape hoist house at the collar of the mine's main ventilation exhaust borehole (fig. 12). The detection

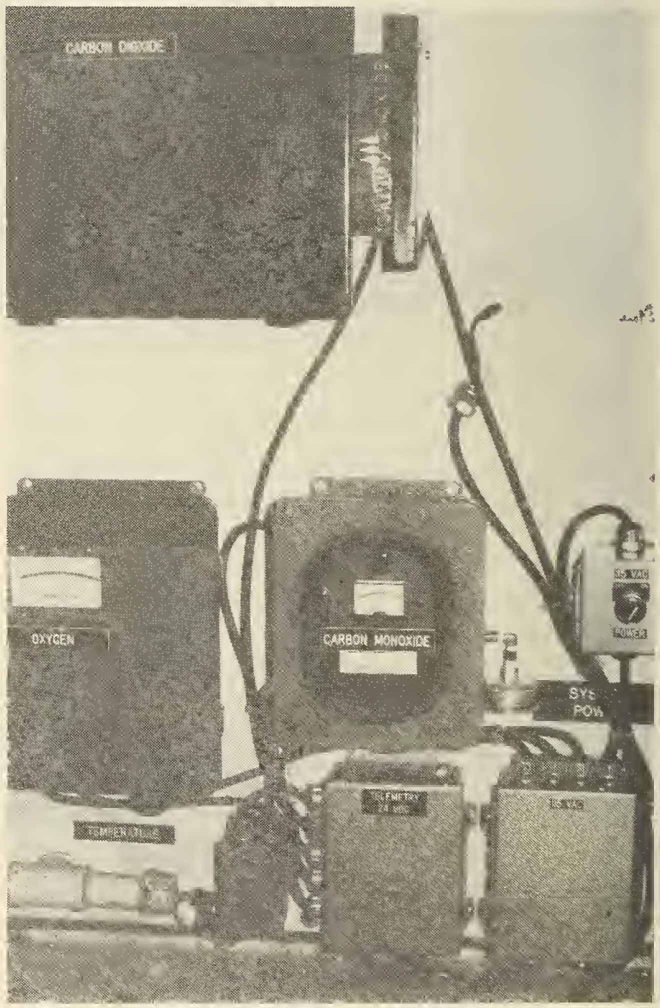

FIGURE 13. - Spontaneous fire warning system detection instruments.

instruments, housed in a corrosion-resistant fiberglass enclosure (fig. 13), were supplied mine air through a draw tube linking the enclosure with the ventilation fan cowling (fig. 14). The system was linked by hard wire to strip charts in a guard house approximately 2,000 ft from the borehole (fig. 15).

Signal transmission is provided by a mineworthy telemetry system. Telemetry interface modules are located at each end of the telemetry line; i.e., in the emergency escape hoist house (fig. 16) and the guard house (fig. 17). The system accepts 1- to 0-V inputs for current loops from the detectors. Each wire pair can accommodate from 1 to 48 channels. Operating on a balanced line principle, and incorporating special line filters and protection networks, the system is noise immune and interference free.

The oxygen analyzer used in the earlier test program experienced excessive drift. Consequently, it was replaced by a similar unit from a different vendor. However, this detector also suffered excessive drift and was removed approximately 1 week after installation. A second electrochemical cell carbon monoxide detector was later installed and connected to the former oxygen analyzer's telemetry channel. This redundancy provided an opportunity to observe tracking between the two carbon monoxide detectors.

After 12 months of system operation, the remaining detectors and telemetry system were functioning properly. Chart recordings indicated up to 15-ppm excursions in carbon monoxide values following end-of-shift production blasts (fig. 18). The two CO detectors track very closely, both at low levels and following the production blasts (the traces are slightly offset to facilitate data analysis). These readings have been validated by analyses of air samples collected at the time of the CO readings.

FIGURE 14. - Draw tube supplying mine air from fan cowling to detection instruments.

COMPUTERIZED FIRE DETECTION SYSTEM FOR AN UNDERGROUND TRONA MINE

The trona mines of southwestern Wyoming are similar in layout and operation to deep room-and-pillar coal mines. Typically encompassing thousands of acres, utilizing numerous production sections and miles of belt conveyor, they are so large that physical monitoring of all mine equipment and operations is not feasible.

Fire detection in these and similar metal and nonmetal mines is very difficult because many potential fire hazard areas are not under continuous, or even periodic, observation. The Bureau has developed a fire detection system for settings and conditions of this type and in-mine tests of the system were undertaken at a Wyoming trona mine.

The system represents the addition of a fire detection capability to an existing computerized monitoring and control network the mine had installed previously as an aid to production. The system monitors and controls the conveyors, ventilation fans, mine pumps, power substations, production shafts and hoists, and underground bunker ore levels. Fire detection system costs were significantly reduced by taking full advantage of in-place telemetry and associated control equipment.

FIGURE 15. - Strip chart recorder in guard shack.

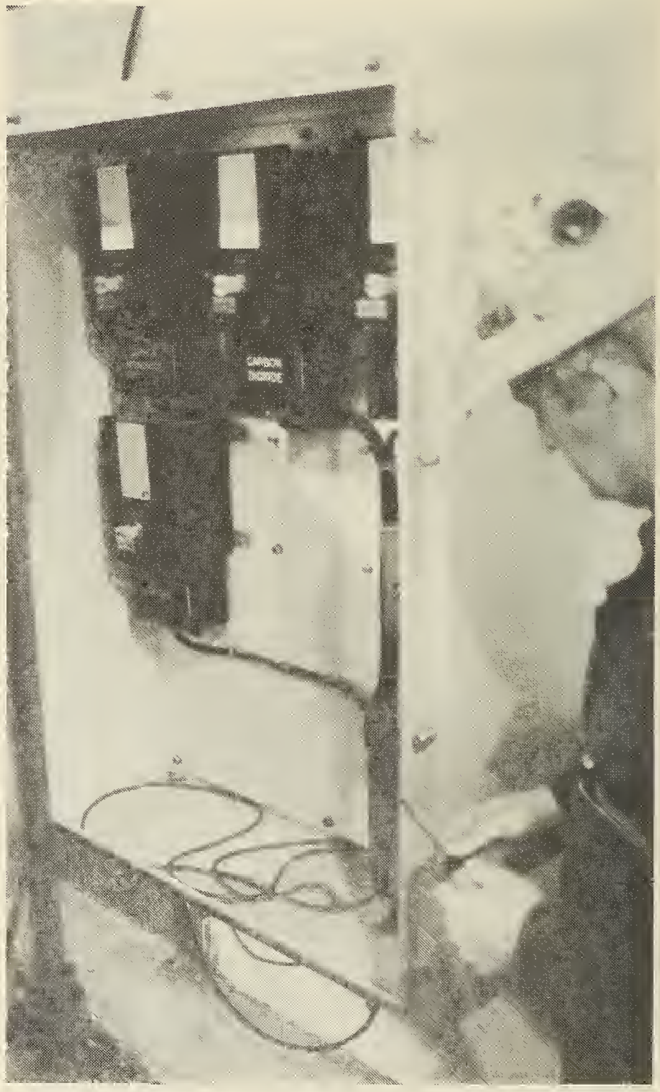

FIGURE 16. - Telemetry interface modules adjacent to detection instruments.

FIGURE 17. - Telemetry interface modules in guard shack.

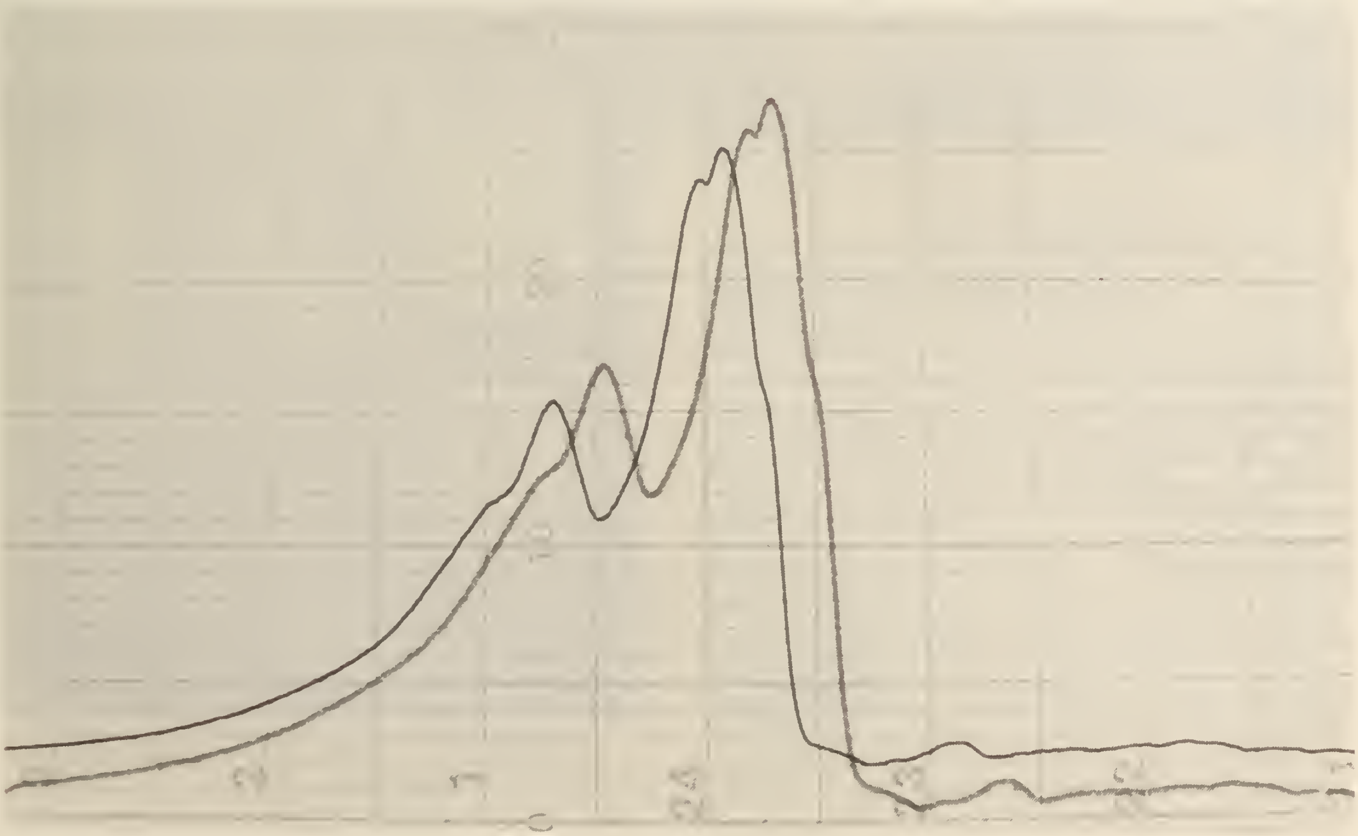

FIGURE 18. - Typical chart recording showing elevated CO levels following end-of-shift blasts.

The system is designed to monitor heat, CO gas, submicron particulates (smoke), and UV radiation levels (flame) at specific locations in the mine in order to detect fires at the earliest possible time.

The fire detection system addition consists of four components: a submaster station and three remote outstations interfaced to fire detectors (fig. 19). The three remotes, A, B, and C, are physically attached to the existing remote units (fig. 20) and utilize the existing remote unit telemetry system to transmit information from the various sensors to the master station. The master station microprocessor (fig. 21) processes the data, initiates alarms and warnings, and sends the processed information to the submaster station to be displayed. The processed information is recorded in the form of paper hard copy on a printer for mine company records.

Remote unit A is located near a belt motor and grease niche area. Fire hazards in this area would include various combustible liquids and greases stored in the grease niche and overheating of belt drive motors. Thermistor line-type heat sensors were mounted above the conveyor belt and over the belt motors to detect overheating (fig. 22). CO and smoke detectors were mounted downwind of the belt motors (fig. 23). The grease niche area is being monitored by two UV detectors (fig. 24).

Remote unit B is interfaced with the same type of sensors as remote unit A with the exception of the two heat sensors. Remote unit C is interfaced to the same types of detectors as remote unit A with the exception of the two UV detectors.

All analog detector signals (smoke and CO) are converted to digital form by an analog-to-digital converter and are transmitted to the submaster along with the various contact closures and dc signals already in digital

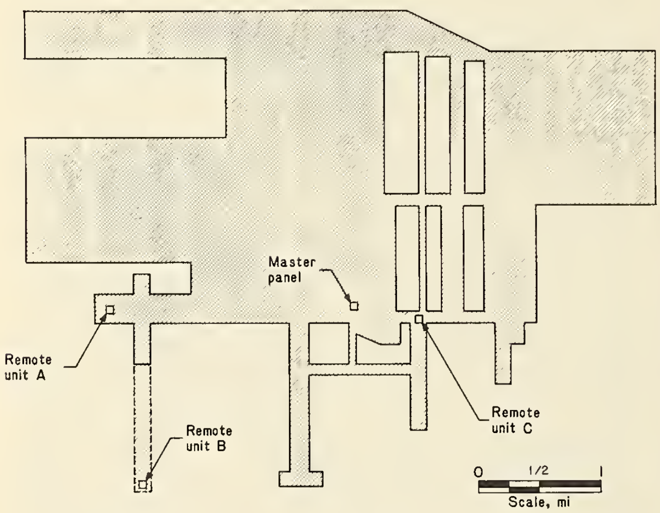

FIGURE 19. - Layout of major elements of trona mine fire detection system.

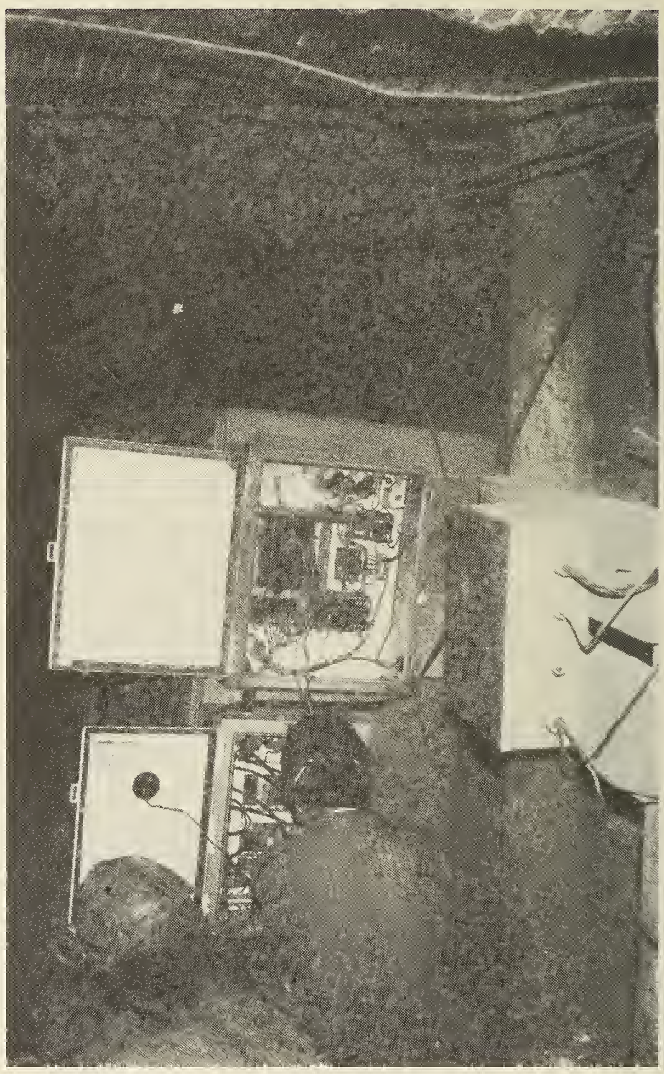

FIGURE 20. - Added remote unit A attached to existing remote unit.

FIGURE 21. - Master station.

form. The analog-to-digital conversion of the analog signals is accomplished by an incremental charge balancing technique.

The telemetry system within the remote units transmits all signals received from the fire detectors to the master station via FSK tone (frequency shift key tone modulation) transmission when called by the microprocessor located in the master station.

The transmitted data are temporarily stored and analyzed by the control microprocessor located in the master station. The submaster station serves as an alarm setpoint control for the microprocessor, a present time status display of processed data, and an alarm annunciator. The alarm set point controls are digital thumb wheels that are used to set the desired alarm level for each measured variable. When the telemetered signal exceeds the set thumb wheel alarm level, the microprocessor initiates an alarm at the submaster station, which corresponds to the remote unit area and type of detector experiencing an alarm. Deactivation of the alarm is automatic when the telemetered variable drops below the setpoint level. The microprocessor also

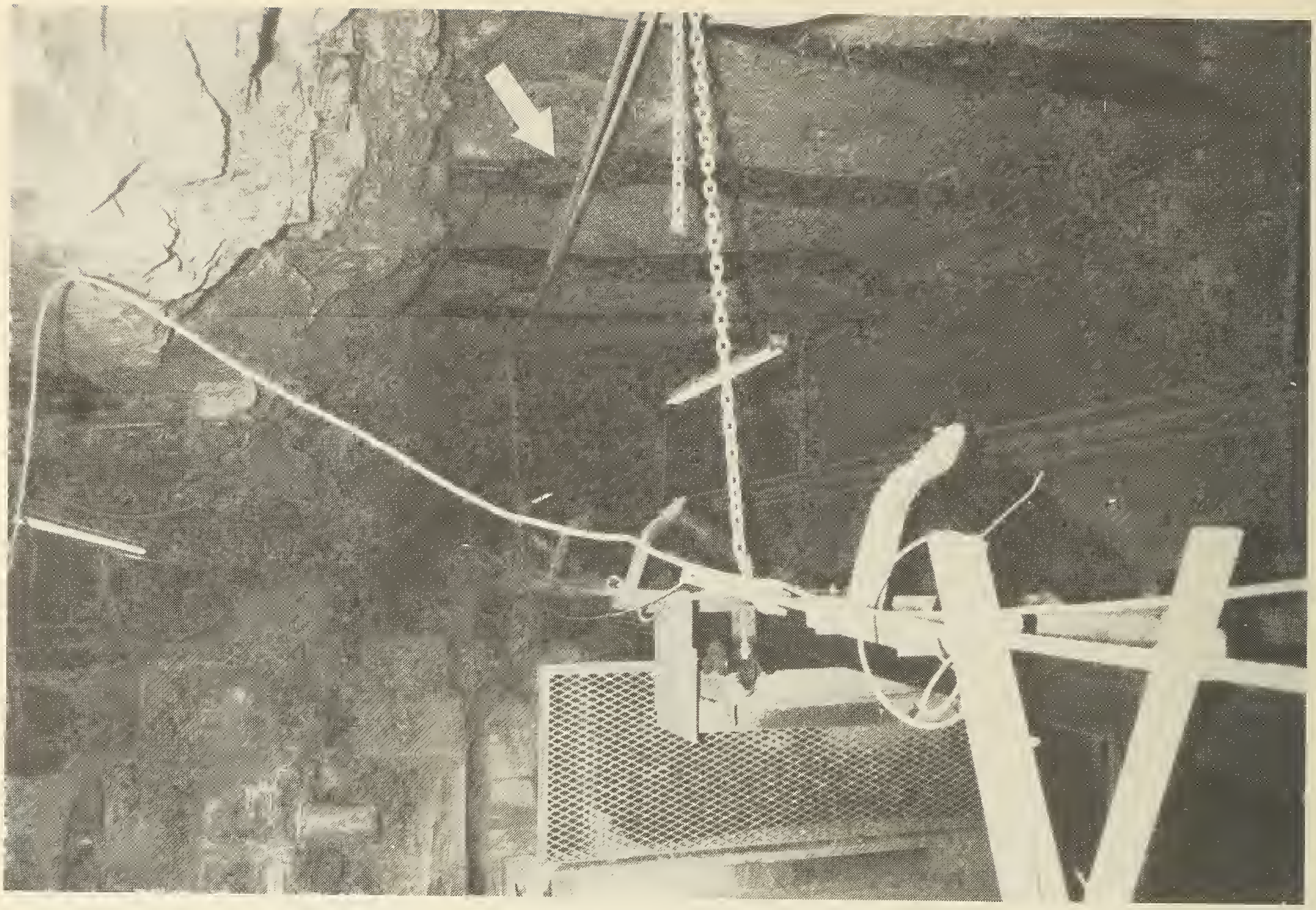

FIGURE 22. - Thermistor line-type detection at conveyor drive.

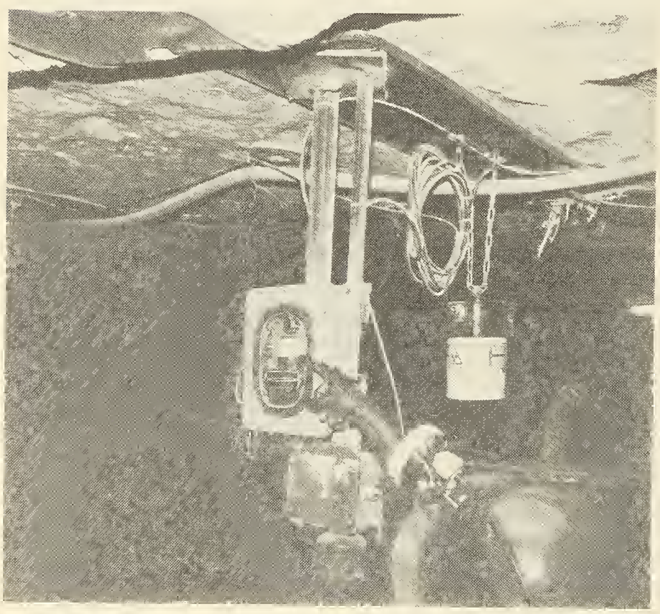

FIGURE 23. - Carbon monoxide and smoke detection instruments located downstream of the conveyor drive.

senses which contact closures are open or closed and transmits the proper alarm or normal mode to the submaster station.

All data received by the submaster station from the microprocessor in the master are recorded by a printer on paper. An alarm-status logger is provided to record sensor status of the various remote units in the mine for the mine company's records. The printer provides an easy to read formatted output. CO levels and smoke particle levels are recorded automatically at 1-h intervals for a period of 24 h and are summarized at midnight of each day. Any alarm conditions will cause the printer to record data instantly at 10-min intervals until the alarm condition subsides.

The system has operated continuously since its installation in 1981 without hardware or software failure.

FIGURE 24. - Ultraviolet flame detector in grease niche area.

CONCLUSIONS

The elapsed time between the onset of a fire and its detection is critical because fires tend to grow in size and intensity with time. Early fire detection and warning permit the initiation of a mine's emergency plan (evacuation, fire fighting, etc.) while the fire is still small, or ideally, while it is still in the incipient stage. Fire detection and warning systems, utilizing sensitive heat, flame, smoke, and gas analyzers, provide the most rapid and reliable indication of a developing fire. Testing of prototype equipment in a variety of mine settings has highlighted both deficiencies and advantages of various detection instruments and telemetry systems.

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APPENDIX

THERMISTOR STRIP SHAFT FIRE DETECTOR

The thermistor strip detection system selected for the salt mine shaft was the Alison Control A888-M106 Fire Detection System.

The control unit is housed in a National Electrical Manufacturers Association (NEMA) 12 enclosure. A separate annunciator is provided in a NEMA 9 enclosure. The system provides two independent, adjustable levels of alarm (prealarm and alarm) that are annunciated at both the control unit and annunciator. The location of the hotspot is also indicated in feet above or below ground level at the annunciator.

The sensor is completely supervised. An abnormal condition is indicated at the control unit and annunciator if an open or short occurs anywhere along the entire length of the sensor. All interconnections between the control unit and annunciator are also supervised.

The A888-M106 system requires 115±10 V ac input power. The maximum power dissipation is 300 W.

The detection cable operates on 24 V dc generated by an internal ferroresonant power supply. Should the system lose ac input power, the power supply is automatically disconnected and standby batteries (located at the bottom of the control unit) are automatically switched in. The batteries are sufficient to power the system for 24 h in standby followed by 1 h in alarm. The system contains a battery charger that automatically maintains the batteries fully charged when ac power is present.

The annunciator is powered from the control unit at 24 V dc and is serviced by the control units backup batteries.

The sensor is composed of thirty 40-ft sections of Alison 9090-100 continuous thermistor cable. This cable consists of stainless steel tubing containing a specially formulated ceramic thermistor core. A center wire is imbedded in the core and runs the entire length of the sensor.

The sensor center-wire-to-case resistance exhibits a negative temperature coefficient. This means that as the temperature increases, the resistance of the sensor decreases exponentially. It is this decrease in resistance that is sensed by the alarm instrumentation. Table A-1 displays the temperature-resistance relationship for 9090-100 series cable. It should be noted that the sensor will detect a high temperature on a short length of the cable as well as a lesser temperature over a longer length of the cable.

TABLE A-1. - Temperature versus resistance for thermistor strip shaft fire detector

Temperature, °F	Resistance, Ω
50	1,000,599,928
100	69,098,544
150	7,397,155
200	1,111,113
250	218,002
300	52,998
350	15,343
400	5,131
450	1,935
500	808
550	368
600	180
650	94
700	52
750	30

The 40-ft sensor sections are connected in series to form two sensor circuits each 600 ft (15 sections) in length. Each 600-ft circuit is monitored separately. The two circuits meet at an elevation of 580 ft where they are terminated in a stainless steel junction box. Stainless steel junction boxes are also provided at the -1,180- and +20-ft elevations to terminate the other ends of each sensor circuit. The entire sensor length and all three junction boxes are coated with a heavy polymer jacket for further protection from the corrosive atmosphere.

The 30 detector cable sections were provided by the vendor in ten 120-ft lengths. Three 40-ft sections were factory spliced to produce each 120-ft length. The factory splices were sealed using a heavy duty heat shrink jacket.

The center conductor at both ends of each sensor circuit is connected to the control unit by single conductor shielded cable. The sensor case is connected to the control unit via the shield.

Each sensor circuit is monitored by a detection panel and a hotspot panel. The upper and lower circuits share common prealarm, alarm, and hotspot indicators, making the two circuits appear as one.

The hotspot panel provides a 5.6 V dc voltage clamp that determines the sensor center-conductor-to-case voltage at normal ambient temperatures. Each hot-spot panel generates a linear 0 to 10 V dc analog voltage that is indicative of the hotspot location for its associated sensor circuit. A special combining circuit selects the output from the circuit that is in alarm and converts it to the proper analog voltage (-18 V dc to +2 V dc) to drive the hotspot location meter at the annunciator. If both circuits are simultaneously in alarm, the lower circuit overrides the upper circuit.

If a large section of sensor is heated, the hotspot circuitry tends to indicate the edge of the hotspot closest to the excited end of the sensor (-600-ft elevation). The hotspot indication for a growing fire will drift towards the -600-ft level.

If a section of sensor is heated to the point where the center-conductor-to-case resistance of the sensor falls to the prealarm setting, the amber prealarm indicator is illuminated at the control unit and annunciator. The auxiliary prealarm relay is energized, transferring three customer available form C relay contacts. The hotspot location indicator at the annunciator is also energized. All of these response indicators reset automatically when the sensor resistance rises above the prealarm threshold.

If the sensor is heated to a point where the sensor center-conductor-to-case resistance falls to the alarm setting, the red alarm indicator is illuminated at the control unit and annunciator. The alarm responses reset automatically when the sensor resistance rises above the alarm threshold.

An abnormal condition such as an open or short in the detection cable, an open or short between the detection cable and the control panel, or the loss of ac or dc power is indicated by audible and visual alarms at the control panel and the annunciator.

SUBMICROMETER PARTICULATE (SMOKE) DETECTOR

The submicrometer particulate detector selected for the underground copper mine and underground trona mine fire detection systems was the Anglo American Electronics Laboratory/Wormald Electronics Becon MK IV ionization type combustion particle detector.

Externally the detector is cylindrical in shape, 10 in. in total height, and 6-1/8 in. in diameter (refer to figures 1 and 2 in the main text). A cylindrical cap having a height of 3-1/2 in and a diameter of 7-1/4 in, which houses the power terminal connectors and test socket, is mounted at the top of the detector. A supension eye ring is affixed to the top of the cap to facilitate the hanging of the detector in the fire hazard area. Because of the highly humid and corrosive underground mine environment, the cylindrical outer casing of the Becon detector is made from nylon-dipped stainless steel to ensure detector longevity and to provide a radiation shield.

Towards the lower end of the Becon detector are vertical rectangular ports, which allow the mine air to enter the ionization chamber. The ports in the stainless steel shield are internally overlapped by a nylon-dipped stainless steel baffle plate, which shields the areas outside the detector from direct radiation, reduces effects of high velocity airflow in the ionization chamber, and causes a mixing of the mine air inside the ionization chamber.

Internally the Becon MK IV particle detector is comprised of a shielded single ionization chamber, a radioactive source, an ion collecting electrode (grid), and a current amplifier. Because of the inherent corrosive nature of the underground mine atmosphere, all internal components of the detector are made of plastic or are hermetically sealed.

The radiation source, which ionizes the air within the ionization chamber, is a sealed glass vial containing 5 mCi of krypton 85 gas. The vial is connected to the grid inside the ionization chamber by two cable ties.

The ionization chamber (conducting plastic chamber case) is constructed from conducting plastic and completely encircles the grid, also made of conducting plastic. The plastic chamber case is cylindrical in shape, but the circumference of its walls is not continuous. Instead, the wall is constructed from a number of overlapping curved rectangular plates of conducting plastic. These plastic plates are affixed to the disk-shaped base of the chamber case at two alternating radii about the mean circumference of the chamber. The longer edges of the rectangular plates run parallel to the axis of the chamber case. This staggering of the sides of the chamber case wall allows mine air to enter the chamber and causes further baffling of the mine air velocity. The plastic chamber case of the ionization chamber acts as the ground electrode with respect to the grid, which is the negative electrode. Because the plastic chamber case along with the conducting plastic upper case are at ground potential they electrically shield the ionization chamber and all internal electronics from electromagnetic radiation external to the detector.

The hermetically sealed amplifier electronics and the grid are electrically isolated from the conducting plastic cases, by a deep annular grooved insulator and conductive plastic guard ring. The annular grooves are present to create the longest possible leakage path between the grid and the case. Electrical leakage could occur if high humidity saturates the inside of the detector with moisture or if a conductive dust is present in the mine atmosphere and eventually settles within the detector. The annular grooved insulator also serves the purpose of supporting the grid and amplifier electronics. The guard ring prevents leakage, by its connection to the non-inverting terminal of the operational amplifier. The inverting terminal of the operational amplifier, which is connected to the grid, is maintained at the same potential as the non-inverting terminal, therefore no potential difference can exist between the guard ring and the grid, which results in no current flow.

The Becon MK IV detector is a single ionization chamber analog output particle detector. The conducting plastic chamber case and the grid are separated by a potential difference of approximately 10 V. This potential difference, with ionized air as the medium, produces an ionization chamber base current of approximately 0.5 nA. The 5-mCi krypton 85 beta radiation source (half-life of 10.8 yr) is used to ionize inflow air. The ionization current across the ionization chamber is adjusted by varying the potential across the case and the grid to yield an ionization current level proportional to a -0.9-mA output current. This base ionization current level corresponds to the particle concentration in normal ambient mine air.

The potential difference between the case and the grid remains essentially constant, however, the ionization current will vary depending upon the size and concentration of particles carried by the inflow air into the ionization chamber.

A charged smoke particle is much heavier than an air molecule, therefore its drift velocity due to the potential between the ionization chamber wall (case) and the grid is very small compared to the convective airflow velocity. The smoke particle also has a much larger surface area than an air molecule, which reduces the mean free path between collisions of the ions responsible for current flow, allowing for greater numbers of positive ion and electron recombinations. Because of recombination, the electron and ion mobility are reduced, which results in a detectable decrease in the ionization current.

A reduction in the ionization current corresponds to a similar reduction in the output of current from the current amplifier. The ionization current and therefore the output current are varied by adjusting a potentiometer that is accessible through a hole in the outer casing of the detector. A capacitor ensures the stability of the current output and supplies the necessary feedback to maintain correct circuit operation when connected to any high output load capacitance.

In order to prevent internal leakage between the grid and the chamber case because of dust accumulations, a circular guard ring is installed between the case and the grid. Any electrical leakage between the grid and the casing would result in a reduced current flow from the grid to the current amplifier and cause an erroneous output current. A potentiometer is adjusted so as to maintain an input offset voltage of approximately 0 V.

Because there is no potential difference between the guard ring and the grid, no current can leak between the two, thereby the grid is electrically isolated from the chamber case.

Humidity, which causes precipitation of moisture on the insulation material surrounding the hermetically sealed electronics, can also cause electrical leakage between the grid and the chamber case. However, because of the strategic location of the current amplifier within the component box, the heat generated by the amplifier keeps the insulator essentially dry around the grid area. Though other components of the detector may be covered with moisture, no current can leak across the insulator to the grid.

The location for mounting the Becon MK IV detector should be near or on the downwind side of a potential fire hazard area, however the ventilation air velocity in the chosen area should not exceed 6 m/s.

Input power requirements are -15 V dc, -5.5 mA dc. A four-conductor shielded cable should be used to provide for the input power and output signal.

Because the Becon MK IV detector has no moving parts, very little maintenance is necessary. Periodic examination of the electrical cable for breaks or frays and calibration are all that is required.

Because of the natural decay of the krypton 85 radiation source (half-life 10.8 yr), the output current will drop as the source decays with age. Therefore, calibration according to the previous section should be carried out annually to ensure proper and consistent operation. This calibration adjustment can compensate for an approximate 50 pct reduction in the strength of the source. Because of this reduction in source strength, the source should be replaced at some time approaching the half-life of the krypton 85.

CARBON DIOXIDE DETECTOR FOR SPONTANEOUS COMBUSTION FIRE WARNING

The Anglo American Electronics Laboratory Spanair analyzer was selected for CO_2 detection in the spontaneous combustion fire warning system. The Spanair nondispersive infrared analyzer detects the attenuation of radiation due to molecular absorption by the sample gas. Variations of the basic cell will show gas concentrations of CO, CO_2, CH_2, NO_2, or SO_2. A nichrome filament pulsed at a specified frequency radiates broad-band energy. This energy passes through the sample gas in a reflective optical chamber, through a spectral filter, and is measured by a pyroelectric cell photodetector. The electrical signal output is inversely proportional to the gas concentration. Selectivity to the sample gas is determined by the band-pass spectral filter.

Both analyzer head and power supply are mounted in a 14- by 18-in fiberglass enclosure designed for underground installation. A dust filter is fitted to the sample plenum. No pump or thermal controls of major importance are required. Electrical connection is made in a junction box partitioned from the analyzer. Input power is 110 V ac, 50 to 60 c/s; output is 0 to 1 V dc analog, with system failure indicated by a 0-V output signal. The output signal decreases logarithmically with increasing gas concentration. Although determination of actual gas concentrations require conversion of the

voltage via a calibration curve (provided with each unit), unusual excursions from normal levels are readily apparent on strip charts and can trigger alarms.

In operation, the Spanair analyzer CO_2 signal shows a constant level of about 330 ppm, which is the concentration of CO_2 in normal atmospheric air. As incipient heating occurs in combustible material, large volumes of CO_2 will be given off well before pyrolysis begins. The system will report these changes as a gradual increase in CO_2.

A receiver (surface unit) processes the analyzer output into alarm levels. The chart records input, voltmeter, and system failure signals. For long distance data transmission, a frequency-division multiplex telemetry system is utilized. Several remote analyzer heads can communicate over one balanced transmisison line (two wires and suitable ground).

The only difficulties anticipated were a lack of published performance specifications and a lack of repair parts or maintenance service available from the Republic of South Africa. However, a competent technician can maintain the electronic circuitry and analyzer head with use of the furnished manual. The only anticipated maintenance consists of periodic cleaning of the particulate filter if the environment is dusty. Mirrors should be cleaned every few years to maintain a strong signal. Calibration requires an output adjustment to 1.0 V during nitrogen purge.

Mine fire detection systems are expected to operate under conditions that would normally disable laboratory instruments. Thus, performance data obtained under stable laboratory conditions do not fully predict performance expected for a mine where conditions are harsh and unstable. Laboratory tests were conducted to determine the degree to which the instrument is immune to such harsh and unstable conditions. Conditions that are expected underground and that are reproducible to a certain degree in the laboratory include the following:

1. Line voltage variation between 90 and 140 V ac.
2. Blackouts for long time periods.
3. Changes in temperature between 10° and 40° C.
4. Changes in ambient moisture level between 20 and 95 pct relative humidity.

The analyzer displayed a slight increase in sensitivity to CO_2 concentrations at temperature extremes, however, the problem is considered to be minor. The analyzer is not sensitive to changes in relative humidity or line voltages. Following power interruption, the instrument restabilizes within 1 minute after power is restored.

OVERHEAT DETECTION FOR CONVEYOR DRIVE

Overheat detection for the conveyor drives at the trona mine was provided with Edison Electronics model 377 control and model B fire detection (thermistor) cable. The 377 control is 2-1/2 by 1-3/4 in. in size; is wired through an eight-pin connector to power (24 V dc); contains a detection cable, audio alarm, and lights; and is mounted to electrical terminals inside a 6- by 8-in corrosion resistant box. The model B fire detection cable is a thermistor; that is, a temperature sensitive resistor. The model B cable is tubular, 0.070 in. in total diameter, with a 0.020-in-diam iron wire center conductor imbedded in a 0.010-in-thick layer of metal oxide semiconducting material. It is 20 ft long and operates within the temperature range of -40° to 2,000° F.

The model B fire detection cable is similar to the cable used in the salt mine shaft. It is constructed with a metallic outer sheath and a metal wire as the center conductor. They are electrically isolated from each other by a cylindrical semiconductor layer. The thermistor's resistance between conductors is depicted by a negative temperature coefficient with a drop in resistance that is nearly exponential with a linear increase in temperature. The rate at which the resistance drops and the temperature at which it drops can be altered by varying the type and quality of the semiconductor material.

The semiconductor material used in the Edison model B fire detection cable has a

conductivity between that of a metal and that of an insulator. Within a semiconductor there exists three discrete energy levels that electrons may cross or occupy; the valence band, the energy gap, and the conduction band. If there are unoccupied high energy levels within the valence band or if the valence band flows smoothly into the conduction band, additional kinetic energy can be given to the valence electrons by an applied electric field, resulting in conduction such as in a metal. However, if the valence band of the material is completely full and there exists a large energy gap, such as 6 eV, between the valence band and the conduction band, the material acts as an insulator.

The semiconductor material has a full valance band, an essentially empty conduction band, an energy gap of approximately 1 eV, and behaves as an insulator at room temperature. Unlike an insulator, the semiconductor, when heated, can gain enough thermal energy from its surroundings to allocate electrons from the valence band to the conduction band. The semiconductor's conductivity increases with temperature as more electrons are elevated to the conduction band. Electrons in the conduction band and hole, vacant spots in the crystal lattice of the valence band, are free to move under the influence of an electric field.

The resistance is measured from the center conductor through the temperature-sensitive semiconductor material to the outer conductor. The resistance is equivalent to that of an infinite number of resistors connected in parallel. The Edison 377 control senses the drop in resistance when the model B fire detection cable is heated, by a proportional drop in the potential difference across two conductors of the cable. If the total resistance of the cable is between 38 and 315 Ω, the control senses the voltage proportional to the resistance and activates the fire alarm via two transistors that are turned on by an operational amplifier. If on the other hand the resistance between the two conductors of the thermistor is less than 38 Ω, the control senses a lower porportional voltage through a second operational amplifier. This operational amplifier turns on several transistors that activate the cable fault light and lock out the alarm circuit.

ULTRAVIOLET FLAME DETECTION

The DetTronics U7602 ultraviolet (UV) flame detector was selected for fire detection in the grease niches at the trona mine. This detector responds to the wavelengths of light given off by a fire in the UV range of 1,850 to 2,450 Å. The electronics are housed in an explosion-proof enclosure 8.91 in. in total length, constructed of two screw-together coaxial cylinders--one of 4.84-in length and 2.3-in diam, and the other of 4.07-in length and 3.25-in diam. The UV viewing area is a 90° cone. Input voltage is 120 V ac with a maximum power consumption of 3.0 W. Two digital alarm modes are provided: one closed relay for fire alarm and one open relay for dirty lens alert.

The DetTronics UV detector utilizes a Geiger-Mueller type tube to sense UV radiation emitted from a fire. A typical Geiger-Mueller tube is constructed with a wire anode, which operates between 160 and 250 V above the cathode. The tube is sealed from the air and filled with an inert gas such as argon or helium. Light can enter through only one end of the tube; all other sides are optically isolated.

When UV light passes into the tube, electrons are knocked off the gas atoms and ions are created. The electrons are accelerated to the anode because of the applied electric field and in turn knock off more electrons from the gas atoms, resulting in an avalanche effect. The ions move to the cathode and electrons to the anode causing the tube to conduct. However, when all the possible ions and electrons have been attracted to their respective electrodes, conduction ceases. Therefore a quenching circuit is necessary to allow the positive ions and electrons to recombine and reactivate the tube.

When the tube conducts it draws down the voltage across a capacitor. The extinguish voltage on the detector is in the region of 160 V, a level at which the ionization processes that support the discharge can no longer be maintained. At this point, the tube will stop conducting and the capacitor will recharge through a resistor that is a current limiting resistor. As the capacitor recharges, it will reach a voltage level in the vicinity of 250 V, which is the normal striking or starting voltage of the tube. If UV radiation of sufficient intensity is present at this moment, the tube will fire again, and this process will be repeated over and over as long as radiation is present. The more intense the radiation the more frequent the discharge rate of the detector.

The fire warning relay is closed when 25 or more discharges occur per second.

The DetTronics U7602 detector is also equipped with an UV test lamp that monitors the integrity of the optical lens and deenergizes a relay when the surfaces become obstructed with oil, dirt, or dust. The UV test lamp emits UV radiation that passes through the lens, reflects off a beveled reflecting ring mirror, passes back through the lens and into the tube.

CARBON MONOXIDE DETECTION

Carbon monoxide detection for the spontaneous combustion fire warning system and the trona mine fire detection system was provided by the Energetic Sciences Ecolyzer 4000 and the MSA 571.

Both the MSA 571 and the Ecolyzer 4000 are CO detectors that utilize the electrochemical properties of a fuel cell to sense CO. Input power to both of these detectors is 120 V ac. The electrochemical sensor is constructed of three electrodes--the sensing electrode, the reference electrode, and the counter electrode--all suspended in an acid solution. The materials to be chemically reacted are CO and oxygen gases from the mine's ambient air. These gases diffuse into the acid (or in the case of the Ecolyzer 4000 are pumped into the fuel cell by an air pump) solution and ionize. Refer to the following half reactions:

$$2\,(CO + H_2O) = 2CO_2 + 4H^+ + 4e^-$$

$$\underline{O_2 + 4H^+ + 4e^- = 2H_2O}.$$

$$2CO + O_2 = 2CO_2$$

The CO is electrochemically oxidized at the sensing electrode while oxygen reduction occurs at the counter electrode. The ion concentration in the acid solution because of the dissolved gases is proportional to the concentration of CO in the air; likewise, the current flow through the cell is proportional to the ion concentration in the solution. Therefore, the current flow through the cell is proportional to the CO content of the air. This current flow is then amplified and compensated for temperature before it is sent to the sensor control.

The MSA 571 and Ecolyzer 4000 CO detectors are very similar in their function. Their input amplifiers generate a 1-V full-scale analog signal output from the signal received from the sensor cells. The input amplifier drives a meter on the detector's front panel and also provides a 0- to 1-V output proportional to the CO concentration. Operational amplifiers used as voltage comparators monitor the output voltage of the input amplifier. When this output voltage reaches a level proportional to 20 ppm, the warning relay activates; at a level proportional to 50 ppm, the alarm relay activates.

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